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Combustion Oscillation in a Staged LPP Combustor

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1 Summary

The presence of combustion oscillation, caused by self amplification of the pressure and heat release fields, is very common within Lean Premixed Prevaporised (LPP) combustors. After suffering significant structural damage from oscillations of this type, an axially staged combustor was subjected to a programme of diagnostic testing to establish a series of safe running conditions. Using fuel staging to vary the local air to fuel ratios (AFR), a series of conditions exhibiting much reduced levels of oscillation were identified.

2 Introduction

Combustion oscillation occurs when the heat release of the flame within a combustor couples with the dynamic pressure field. Generally, if the heat release and pressure fluctuations are in phase, then a positive feedback loop is created and self-amplification will occur. The corresponding pressure oscillations increase rapidly to a finite limit. The amplitude of these oscillations can result in increased noise and damage to, or destruction of, the combustor.

The move towards advanced low emissions combustors has made this phenomenon more common. Techniques such as LPP combustion rely upon burning a weak flame to minimise the production of nitrogen oxides (NO_X) by maintaining low combustion temperatures.

To provide the required combustion most of the air enters the combustor with the fuel, consequently it is normal for there to be no primary, secondary or dilution holes. This arrangement essentially provides a resonant geometry that is highly susceptible to combustion oscillation.

A programme of research, named LOWNOX, was established to investigate methods for reducing NOx emissions from gas turbine aircraft engines. The European Union sponsored programme involved a consortium of 23 organisations from around Europe including industrial companies, research establishments and universities.

It is commonly acknowledged that, subject to limitations, NOx production and combustion efficiency increase with combustor length. Thus a programme of high pressure testing, Part 1, was proposed to determine the optimum length and volume for an LPP combustor of a specific architecture. During these tests, combustion oscillations were encountered of such intensity that the test combustor was damaged preventing the completion of the programme.

To allow the programme to proceed, a series of diagnostic tests, Part 2, was identified to provide a set of safe running conditions. The combustor was repaired and strengthened and re-tested to establish a safe operating envelope.

3 Overview

The unit tested was an axially staged LPP three-sector combustor; a diagrammatical representation is shown in Figure 1. The combustor was required to operate within the constraints of Engine E, the operating conditions of which are listed in Table 1 for the full size 24-sector combustor. Engine E[1] was a theoretical prediction, produced in the early 1990s during the first LOWNOX phase, of an engine cycle for a large subsonic civil turbofan engine with a service entry date of around 2000. The test combustor was supported at its exit in a high pressure test rig[2] that had initially been selected for its novel capability for internal mapping of the hot gas species. The installation provided the combustor with air, conditioned to the required temperature and pressure, from an entry plenum. The exhaust gasses then vented into a large exhaust drum on to which was mounted the internal traversing gas sampling probe. The arrangement is illustrated in Figure 2.

The combustor was designed to pass approximately half of the total air flow through the main ducts, proportionately less through the pilot ducts and the remaining one third was used for cooling. These proportions were determined by the need to maintain the stoichiometry of the main and pilot zones within certain limits to control the flame temperature and NO_X levels.

The combustor is shown assembled, complete with the LPP ducts, in Figure 3. Each of the three sectors had one main and one pilot LPP duct. Nickel alloy cooling tiles, inset in Figure 3, were fitted to the upper and lower faces of the casing to facilitate the efficient use of cooling air. The casing incorporated removable windows in the main zone for observation of the flame. If required, the windows could be replaced with metal panels to provide greater structural integrity.

The main LPP ducts were mounted outboard of the pilot zone and angled towards the engine axis. Each duct consisted of two co-axial air passages incorporating axial swirlers. The fuel was injected radially into the inner passage through a number of small holes.

The pilot LPP ducts were mounted parallel to the engine axis and some distance forward of the main ducts. Radial fuel injection into a swirling airflow was again employed. A fraction of the fuel was injected close to the duct exit via a centrally positioned pressure jet atomiser to provide combustion stability.

Previous single sector test experience had shown that both the pilot and main LPP ducts were prone to oscillatory

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combustion instability. Therefore, additional instrumentation was incorporated into the design to obtain as much dynamic pressure information as possible. This consisted of pressure tappings connected to pressure transducers located close to the rig. Certain processing treatments were applied to the measurements during testing to provide the necessary information to progress the trial, whereas, more thorough analysis treatments were applied following the tests.

During the Part 1 tests, conducted at DERA, pressure oscillations were encountered. At the Engine E Approach condition, one of the two sidewall mounted quartz windows failed. Both windows were replaced with the alternative metal panels prior to the next test run. However, pressure oscillations were again observed at the same test condition but, on this occasion, they were at increased amplitude and further damage resulted. The damage to one of the sidewall panels is illustrated in Figure 4. The panel has been bent inwards following failure along three sides of the mounting. Both combustor sidewalls were distorted and localised cracking was observed on a number of combustor components.

The combustor was repaired and reinforced, Figure 5, prior to the start of the second phase of tests.

4 Test Conditions

The combustor was required to operate within the constraints of Engine E conditions, Table 1, up to pressures and temperatures of 47bar and 917K. Some scaling of the combustor was required for it to match the test facility combustor entry capability and this is reflected in the test conditions listed in Table 2.

At the lower power conditions the fuel had to be staged to obtain suitable flame temperatures for low NOx and high efficiency. At the Idle and Descent conditions the combustor was operated using only the pilot injectors. At the Approach condition a full engine combustor would operate with all pilots and 1 in 4 main injectors fuelled to optimise the zone temperatures. With the three-sector test combustor, one of the main injectors (the central one to minimise wall effects) was fuelled with the appropriate flow to simulate 1 in 4 staging. To identify the safe areas of operation, further staging and fuel management was employed to alter the local AFRs that have a direct effect on the magnitude of oscillation.

5 Analysis

The levels of oscillation encountered at various AFRs and engine conditions were assessed to determine the safest conditions for operation. The combustor pressure instrumentation was used to determine the fuelling arrangement that gave the greatest reduction in acoustic power.

A total of eleven tappings was installed on the combustor, ten on the headplates, Figure 6, and one at the exit plane of the combustor. Three other tappings, external to the combustor, were used for reference. These monitored dynamic pressures in the entry plenum, in the central main LPP duct and the transducer reference pressure. The pressure lines from tapping to transducer were each 2m long and 1.08mm in bore. The system was calibrated at frequencies up to 2kHz. Good agreement with theoretical prediction was achieved providing confidence that the application of any corrections would be valid[3]. Good resolution of the dynamic pressure component was achieved by using low range transducers in a differential mode. The entry plenum pressure was used for the reference with line damping to avoid the transmission of any pressure perturbations. The amplified transducer signals were recorded on a personal computer based data acquisition system capable of operation in the following two modes:

Multichannel : up to 14 channels, each sampled at 4kHz with a 1.35kHz low pass elliptical filter.

7-channel : 7 channels, each sampled at 8kHz with a 2.5kHz low pass elliptical filter.

During testing, the data were presented graphically to provide early warning of the onset of significant oscillations. Post-test data processing, to determine the power spectra and the levels of acoustic power, was used to characterise the compound waveforms and, or, identify low amplitude resonances.

At the Approach condition during Part 1 testing, a resonance, at 1230Hz was detected when the pilot ducts were fuelled showing peak-to-peak values of 5kPa and 15kPa respectively for the two test runs. When the central main duct was also fuelled the peak-to-peak measurements increased to 37kPa and the frequency dropped to 680Hz. The power spectra is shown in Figure 7 (this, and the subsequent illustrations of oscillation characteristics are presented as power spectra using data acquired from pressure tapping No 1; arbitrary units have been used for the vertical, power, scale). This 680Hz frequency is consistent with a longitudinal quarter wave resonance of the combustor based on the assumption that it approximates to a pipe open at one end. This mode could only propagate if reflections were to have occurred from a sudden expansion at the combustor exit. The standard method of mounting combustors in the test facility provides such an opportunity, Figure 2. The inclusion of a flared exit channel to the combustor, an acoustic horn, may be appropriate to suppress any longitudinal standing waves. The observation of the second harmonic at 1360Hz may be due to a non-linear propagation within the combustor or the pressure tapping tubing, or a combination of both.

On both occasions when damage occurred during the early tests the oscillation characteristics changed. The failure of the glass window resulted in the oscillations ceasing due to the permanent disruption of the feedback loop. The partial failure of the replacement panel resulted in the oscillation frequency changing intermittently from 680Hz to 510Hz as the feedback loop varied due to panel flutter.

During the Part 2 tests, very low level oscillations of 0.4kPa peak-to-peak were present at a frequency of 1160Hz whilst at the Idle condition. These were only revealed following post-test data processing as they were masked by the system noise. The magnitude of these oscillations remained almost constant over a range of AFRs from 18.4 to 29.5.

The pilot flame was then enriched as the combustor was advanced to the Descent condition. Once again, low amplitude oscillation was present. This time the frequency was 1170Hz, Figure 8; the peak-to-peak amplitude of 0.7kPa was again hidden by noise. This mode persisted over a range of AFRs from 18.3 to 27.5, but rose significantly outside this range.

At the Approach condition, the response was similar to that observed during the earlier tests. Initially, only the pilot ducts were fuelled, operating within the safe limits determined at

Decent. Fuelling the central main duct, at 22.5 AFR, again generated a significant oscillation, this time at a frequency of 630Hz. The change in frequency is directly attributable to a reduction in flame temperature of approximately 300K due to changes in running conditions. The second harmonic, at 1260Hz, was also present, Figure 9. The respective peak-to-peak measurements were 13kPa and 7kPa representing ±0.7 and ±0.38% of the combustor inlet pressure. These amplitudes were lower than those measured during the earlier tests. The amplitudes increased dramatically when the main duct AFR dropped below 21.1 or rose above 25.9 whilst maintaining the overall combustor AFR constant.

Two resonant frequencies, namely 470, and 700Hz, were detected at the Cruise condition where the main and pilot AFRs were 31.8 and 31.2 respectively. The predominant 700Hz signal measured 15.1kPa peak-to-peak. As the main was enriched the oscillations at 700Hz increased significantly in magnitude. Operation over a range of main AFRs from 23.8 to 36.1 revealed a significant increase in magnitude, ranging between 20 and 32kPa peak-to-peak at AFRs below 28.3.

Frequencies of 675Hz and 2075Hz were observed at the Climb-out condition whilst varying the main AFR between 33.3 and 25.8 but maintaining the overall AFR constant. At a main AFR of 28.9 the magnitude of the signal at 675Hz was an acceptable 10.1kPa peak-to-peak but rose significantly when the AFR was set at richer levels. The effect of circumferential staging on both pilot and main ducts was investigated. Neither was successful in reducing oscillation in that the former had a minimal effect, whereas, the latter resulted in a sharp increase in magnitude to 19.0kPa peak-to-peak, due possibly to the creation of large thermal gradients. The detrimental effect of thermal gradients may explain why, at similar AFR settings, the operation of all three main ducts resulted in the level of acoustic power being 70% less than when two ducts were fuelled.

At the Take-off condition, oscillations were identified at frequencies of 464, 720 and 1424Hz, Figure 10. The more dominant resonance at 720Hz measured 10.9kPa peak-to-peak. The main fuel flows were again varied whilst maintaining the overall AFR. This level of oscillation only existed between AFRs of 28.1 and 29.6, with peak-to-peak levels rising to 20kPa outside this range. All the frequencies observed differed from those measured when the pilot and main ducts were tested separately on a single sector combustor. Pilot oscillations were observed at 1450Hz with frequencies of 300Hz and 1550Hz measured for the main duct, the latter being attributed to the first longitudinal mode of that combustor.

The oscillation measurements referred to above are average values and were subjected to considerable short-term fluctuation. Two mechanisms of oscillation appeared to co-exist, a constant lower amplitude oscillation periodically overlaid by short bursts of higher amplitude activity. The influence of these short bursts of activity is not fully understood at present.

The phase relationships between the pressure signals were determined at each operating condition for the dominant frequency. Pressure tapping 1, Figure 6, was used as the reference position.

The phase relationships proved to be different for each operating condition and also suggested that a complex series of modal patterns existed within the combustor, featuring both transverse and longitudinal components. These varied considerably with changes in operating condition. The limited data available made it impossible to determine what modes were present. An additional complication in understanding the modal patterns is the acoustic waveguide effect[4] due to temperature gradients between the main and pilot zones and the burning zones associated with each LPP duct.

6 Conclusions

Tests have been carried out on an axially staged LPP combustor to identify the limits for the onset of combustion oscillation. Combustion oscillation was encountered at all the conditions tested but, by varying the local AFR and mapping the intensity of oscillation, a series of safe operating conditions was established. In general, the magnitude of oscillation could be reduced by increasing the main duct AFR whilst maintaining the overall combustor AFR constant by reducing the fuel to the pilot ducts. Operating at the design values of AFR should be possible with adequate safety margins at all the operating conditions with the exception of Take-off. At this condition there is little, or no, safety margin.

At all conditions, where the main ducts were fuelled, the dominant oscillation frequency lay in a band between 675 Hz and 720Hz depending upon the prevailing temperature profiles within the combustor. This is consistent with a longitudinal standing quarter wave within the combustor.

The phase relationships determined from the pressure measurement positions suggested that a complex series of modal patterns existed and that these patterns were different for each operating condition. The limited data available made it impossible to determine what modes were present.

Much empirical work is still required to understand the phenomenon of combustion oscillation.

The present work was supported by the European Commission as part of the Brite-Euram Research Programme 'Low Emission Technology Programme Phase III / LOWNOXIII - part 1' under contract number BRPR-CT95-0122, which is gratefully acknowledged. DERA's participation in this programme was co-funded by the UK DTI (CARAD), whose sponsorship is also gratefully acknowledged.

7 References

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2. Design considerations for NGTE Combustor Test Rig, J B Bullard, DERA, 1982
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4. Fundamentals of Acoustics, 3rd ed., L E Kinsler A R Frey A B Coppens J V Sanders, John Wiley & Sons, 1982

Condition	Thrust	Combustor inlet conditions			AFR	Exit Temp
	%	Temp (K)	Pressure (kPa)	Mass flow (kg/s)		(K)
Idle	7	551	701	33.3	115.11	886
Descent	15	617	1090	47.0	98.90	1110
Approach	30	709	1817	73.1	68.57	1232
Cruise	44	846	1758	60.3	39.91	1672
Climb-out	85	878	4109	140.3	40.83	1683
Take-off	100	917	4760	157.2	36.88	1792

Table 1 Engine E Conditions

Condition	Inlet P	Combustor P	Inlet T	Air Flow	Total Fuel Flow	Main Fuel Flow	Pilot Fuel Flow
	Bar	Bar	K	kg/s	g/s	g/s	g/s
Idle	7.01	6.73	551	3.89	31.7	-	31.7
Descent	9.20	8.83	617	4.33	40.9	-	40.9
Approach	9.20	8.83	709	4.33	66.8	31.4	35.4
Cruise	9.60	9.22	846	3.85	90.0	63.0	27.0
Climb-out	9.60	9.22	850	3.90	89.2	62.4	26.8
Take-off	9.60	9.22	850	3.85	97.8	68.4	29.4

Table 2 Combustor operating conditions

Condition	LPP Duct	AFR Range	Design AFR
Idle	Pilot	29.5 – **18.4**	26
Descent	Pilot	27.5 – **18.3**	22.6
Approach	Pilot	30.5 – 25.2	26.1
	Main	25.9 – **21.1**	23.9
Cruise	Pilot	39.9 – **24.5**	30.4
	Main	36.1 – **28.3**	31.8
Climb-out	Pilot	39.9 – 30.3	31
	Main	33.3 – **28.9**	32.5
Take-off	Pilot	31.9 - **28.1**	28.1
	Main	29.6 - **28.1**	29.4
Note: Values in **bold** indicate the operational limit of the combustor.			

Table 3 Table of AFRs for reduced oscillations

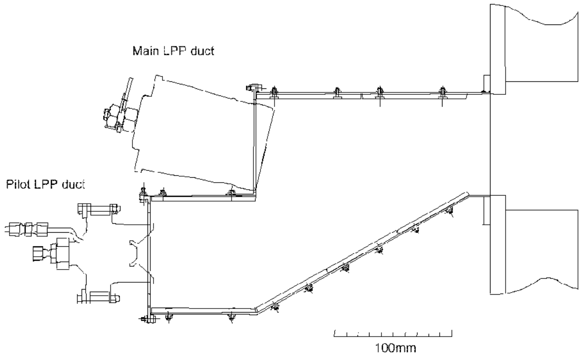

Figure 1 Axially Staged LPP Combustor

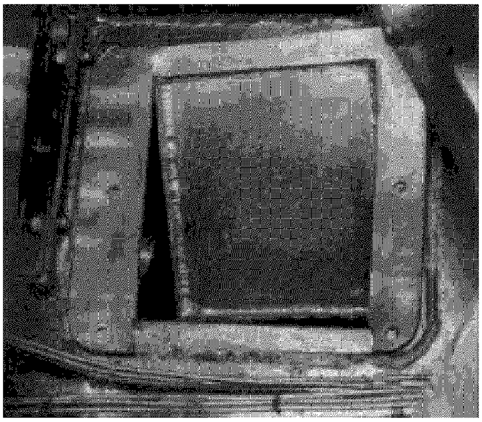

Figure 4 Damage to one of the sidewall panels

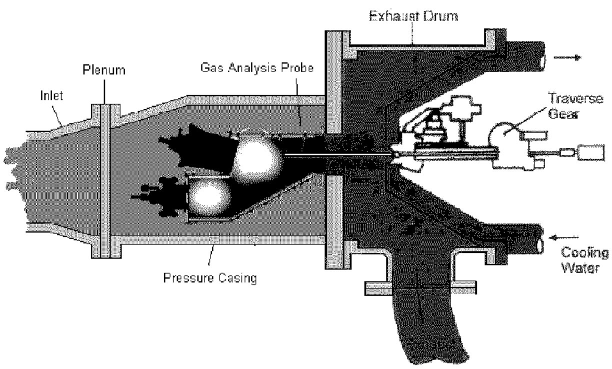

Figure 2 Schematic of Combustor Installation

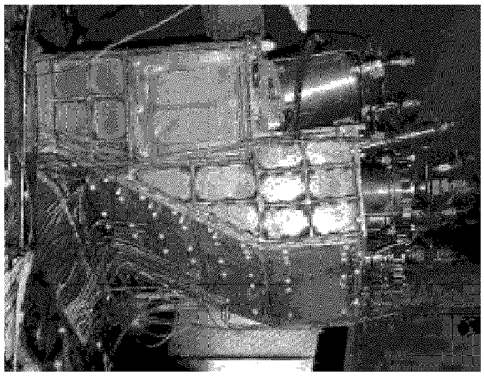

Figure 5 Reinforced Combustor

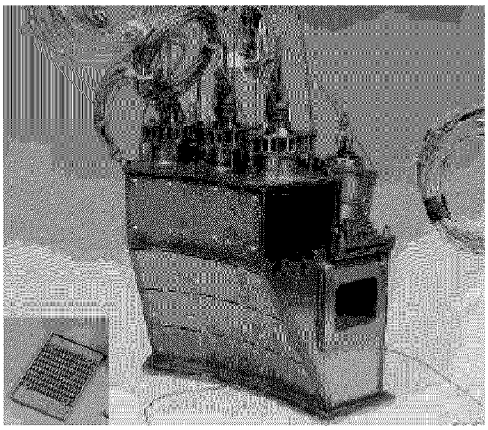

Figure 3 Test Combustor, cooling tile shown in inset

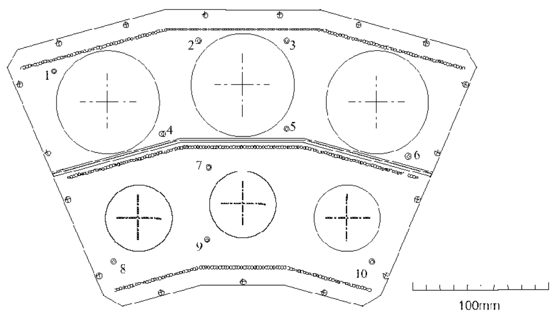

Figure 6 Pressure tapping locations on the combustor headplates

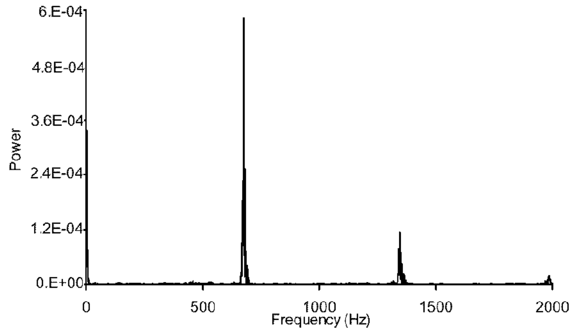

Figure 7 Power Spectra from Approach Condition, Part 1 Tests

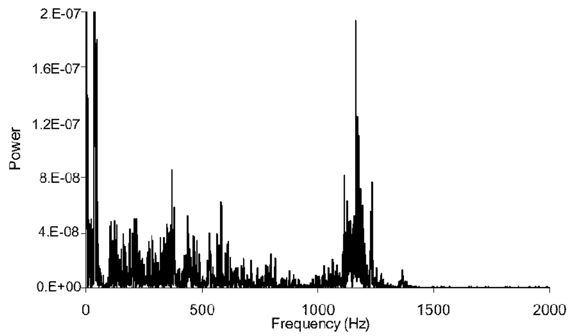

Figure 8 Power Spectra from Descent Condition, Part 2 Tests

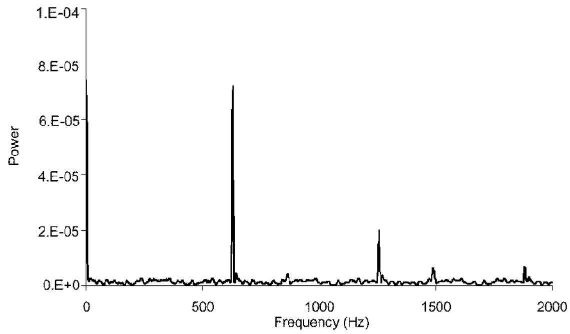

Figure 9 Power Spectra from Approach Condition, Part 2 Tests

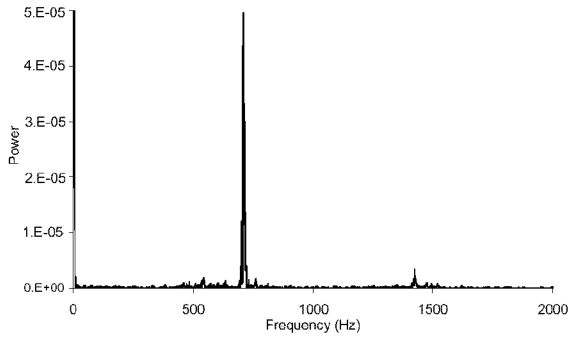

Figure 10 Power Spectra from Take-off Condition, Part 2 Tests

PAPER -18, J. Tilston

Question (U. Vandsburger, USA)

Comment: modeling of acoustics of test rigs like this has proven rather complex, even in cold flows. You get many features which are of the whole rig and not the combustor along. E.g., the effects of a perforated plate instead of a closed boundary.

Why use linear scales on the p' graphs? Nonlinear scaling will show all, rich, features. Some of these will be related to the analysis above.

Reply

The primary purpose of the test program was to establish an envelope of safe combustor operation by identifying the fueling conditions at which damaging levels of oscillation existed. The work was not intended to be a detailed combustion oscillations research exercise. Therefore, it was only necessary to identify the dominant frequencies where the power was greatest. For this purpose, the use of linear power scales is adequate.

Question (S. Candel, France)

What was the mean pressure in the combustor? Where did you place the pressure sensor (or sensors)? If there was more than one sensor, did you measure the phase differences?

Reply

The mean combustor pressure for each test condition is shown in Table 2 of the paper. Eleven pressure sensing points were measured, ten in the combustor head plates and one at the combustor exit (see Section 5 of the paper). The phase relationships were determined and proved to be different for each operating condition, suggesting that complex modal patterns existed. See Section 5 of the paper for additional information.

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